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Away-Side Angular Correlations Associated with Heavy Quark Jets

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Based on: Noronha, Gyulassy, Torrieri, arXiv:0807.1038 [hep-ph]

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Outline

I Motivation: Away-side angular correlations at RHIC

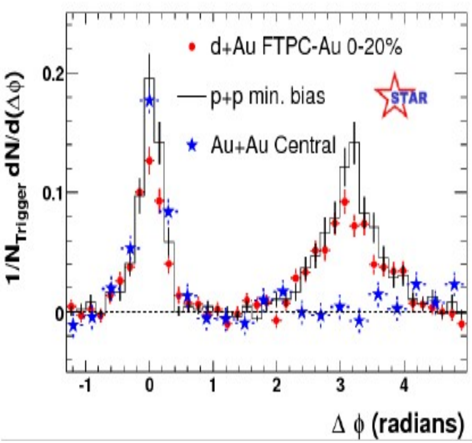
II Holographic Description of Heavy Quarks

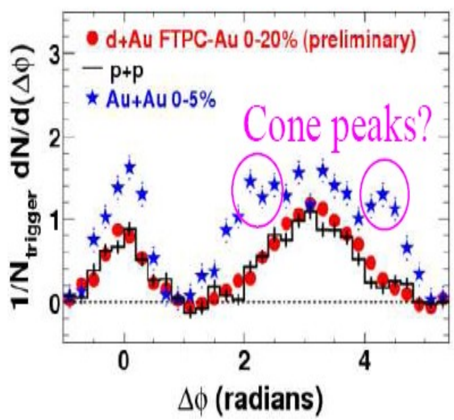
III Computation of Away-side Angular Correlations

IV Conclusions & Outlook

I Away-side Angular Correlations at RHIC

RHIC @ 200 GeV





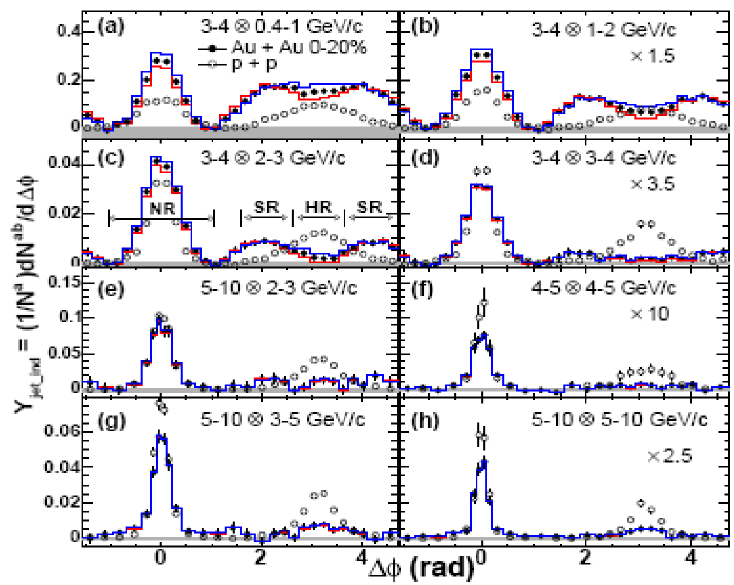
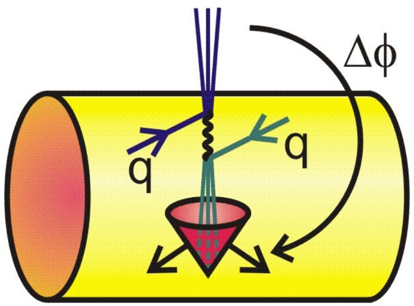


FIG. 6: (Color online) Per-trigger yield versus $\Delta\phi$ for various trigger and partner p_T ($p_T^a \otimes p_T^b$), arranged by increasing pair proxy energy (sum of p_T^a and p_T^b), in $p+p$ and 0-20% Au+Au collisions. The data in several panels are scaled as indicated. Solid histograms (shaded bands) indicate elliptic flow (ZYAM) uncertainties. Arrows in Fig. 6c depict the "Head" region (**HR**), the "Shoulder" region (**SR**) and the "Near-side" region (**NR**).

Signature of conical emission?

H. Stoecker, Nucl.Phys.A750:121-147,2005.
J. Casalderrey-Solana, E. Shuryak, D. Teaney, J.Phys.Conf.Ser.27:22-31,2005 .



Mach's law

$$\boxed{\cos\phi_M = \frac{c_s}{v}}$$

For light partons v ~ 1 then from

$\phi_M \Longrightarrow c_s \Longrightarrow$ EOS !!!!

Time averaged

However, experimentally angle between shoulders nearly independent of:

- Centrality (NO DISTORTION FROM FLOW???)

- Orientation of the trigger particle w.r.t. to reaction plane (UNPUBLISHED PHENIX DATA)

- Collision energy (“CERES MACH CONE PUZZLE”)

- ZYAM ?????

- There's still theoretical uncertainty to what these peaks correspond to ...

See, for instance: I. Vitev, PLB 630, 78 (2005).
V. Koch, A. Majumber, X-N Wang, PRL 96, 172302 (2006).
J. Jia, R. Lacey, arXiv:0806.1225 [nucl-th].
E. Shuryak's mixed phase arguments ...

What would be the most clear evidence for the Mach cone scenario???

IDEALLY, one could check if the angle changes with v according to Mach's law (at least qualitatively)

PROPOSAL: Measure away-side correlations associated with identified heavy quark jets (velocity v can be determined). This would provide a clear and direct test of the Mach cone hypothesis.

Noronha, Gyulassy, Torrieri, arXiv:0807.1038 [hep-ph]

However, heavy quark energy loss in the QGP can be a tricky business ...

See, for instance: Wicks, Horowitz, Djordjevic, Gyulassy, NPA 784, 426 (2007)
Among many other papers ...

BUT, in principle in the sQGP

- Heavy quarks are not ultrarelativistic.

- Collisional energy loss becomes important (perturbative ???)

It would be great if we had an idea of what heavy flavor energy loss looks like in a strongly-coupled plasma which displays hydrodynamical behavior in the deconfined phase with eta/s ~ 1/(4 Pi) ...

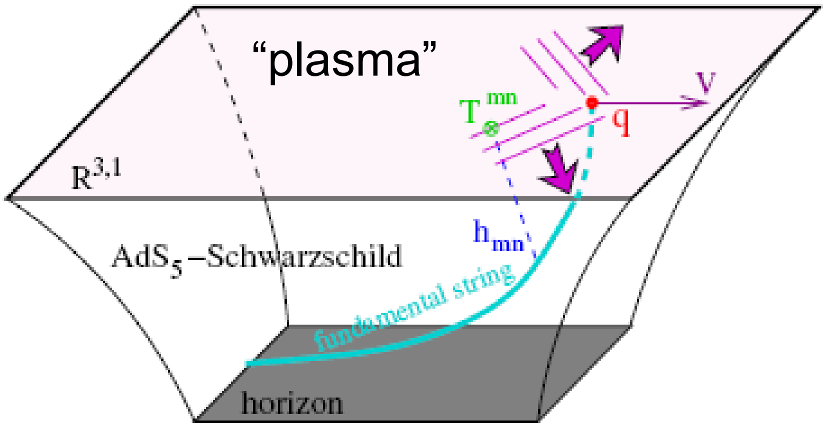
AdS/CFT gives you that and MUCH MORE !!!

II Holographic Description of Heavy Quarks

$$\lambda \gg 1$$
$$N_c \to \infty$$

Heavy quark mass

$$M \gg \sqrt{\lambda}\, T_0$$



Exact solution for $X^{\mu}(\tau, \sigma)$

on $AdS_5 \otimes S_5$

Herzog et al, 2006.
Gubser, 2006.

Friess et al., PRD 75, 106003 (2007).

The result is surprisingly simple ...

Drag force in $\mathcal{N} = 4$ SYM plasma

$$\frac{dp}{dt} = -\frac{\pi}{2}\sqrt{\lambda}\,T_0^2\,v\,\gamma$$

v Heavy quark's velocity

Non-expanding, infinite plasma

Gubser, PRD 74, 126005 (2006).
Herzog et al, JHEP 0607, 013 (2006).
Casalderrey-Solana and Teaney, PRD 74, 085012 (2006).

But, wait, there's more ...

- In fact, AdS/CFT gives us the mind-boggling opportunity to compute the FULL energy momentum tensor of the system = plasma + heavy quark !!!!

Friess et al., PRD 75, 106003 (2007).

- Full analytical results are known for the near-quark region !!!!!

A. Yarom, PRD 75, 105023 (2007); S. Gubser and S. Pufu, NPB 790, 42 (2008).

- It can be shown analytically that the long wavelength modes behave hydrodynamically !

See for instance: Gubser, Yarom, PRD 77, 066007 (2008)

Generically, our (strong but justified) theoretical prejudice is that spacetime surrounding the moving heavy quark may be divided as follows:

1) A Lorentz-contracted Head zone: region very close to the quark where the coherent fields dominate and any sort of hydrodynamics is certainly not valid.

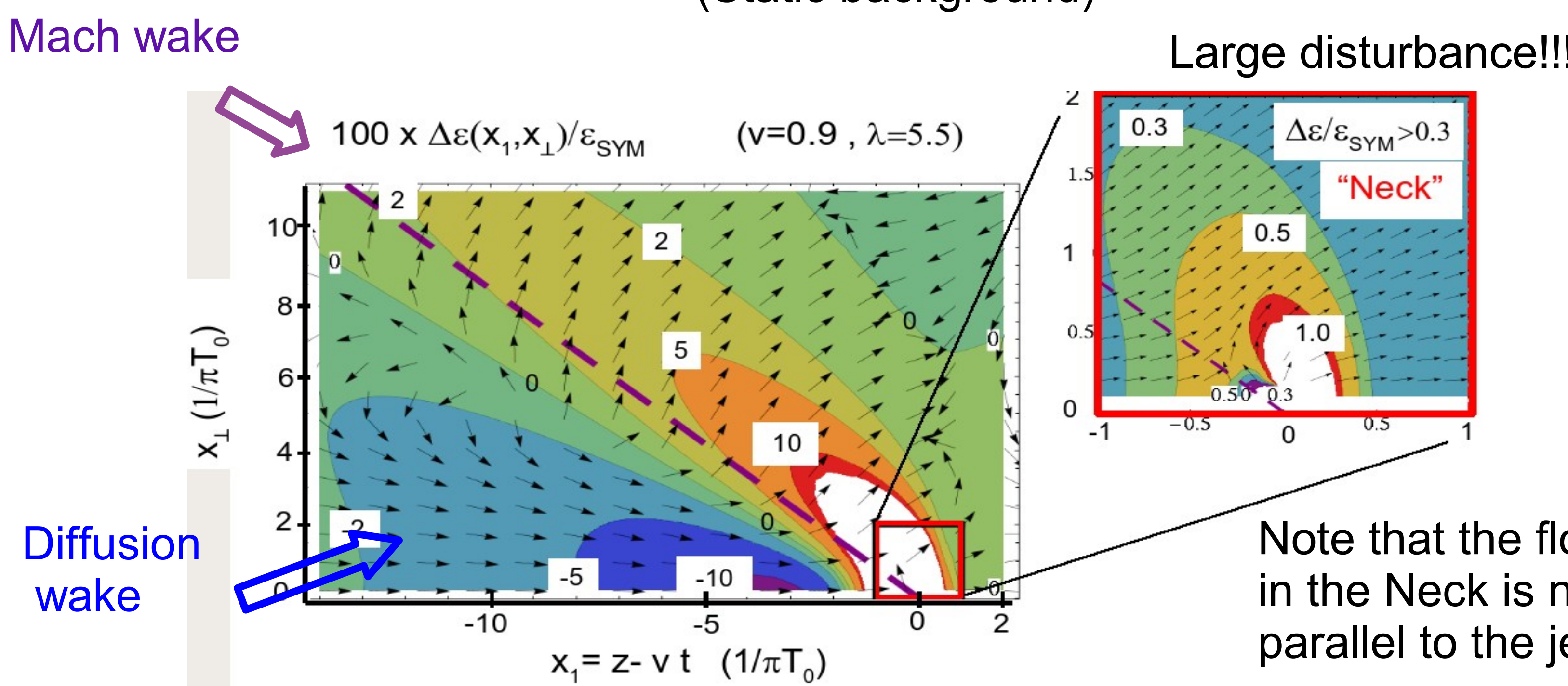
2) The Neck region: a transition region between the head and far zone that is still strongly affected by the coherent Coulomb field and the disturbances caused by the heavy quark is very strong (hydrodynamic behavior ???)

3) The far zone: where hydrodynamics is certainly a good approximation and regular Mach, as well as diffusion wakes, should be found.

See also discussion in J. Casalderrey-Solana, E. Shuryak, D. Teaney, hep-ph/0602183.

From the numerical calculations of Gubser, Pufu and Yarom, PRL 100, 012301 (2008)

(Static background)



Note that the flow in the Neck is not parallel to the jet !!!

Plot from Noronha, Gyulassy, Torrieri, arXiv:0807.1038 [hep-ph]

Some general comments ...

- The head region is assumed to be remain attached to the heavy quark
~ spatial size of the heavy quark cloud

F. Dominguez et al., NPA 811, 197 (2008).

- Neck zone describes the strong medium response of the near-quark region (even if the heavy quark stops in the medium the Neck cannot be neglected because the large energy-momentum in that region will be converted into flow).

- The Mach cone in the far zone is always formed (PHYSICS 101 cannot be avoided :). The diffusion wake is sensitive to the details involving the source term in the hydrodynamic equations.

Understanding some of the details of the AdS/CFT calculations ...

$N_c \to \infty$ $\lambda \gg 1$ EOS: CFT $c_s^2 = 1/3$

$$\boxed{T^{\mu\nu} = T_0^{\mu\nu} + \delta T^{\mu\nu}}$$

Head+
Neck+
Far zone (Mach+
Diff. Wake)

background

$$T_0^{\mu\nu} = \text{diag}(\varepsilon_0, p_0, p_0, p_0)$$

$$p_0 \sim N_c^2 T_0^4$$

However, note that the disturbances caused by the string $\sim \sqrt{\lambda}$

(fluctuations are neglected)

Thus, the relative disturbance w.r.t. to background is $\mathcal{O}(\sqrt{\lambda}/N_c^2)$

(very small number)

Interesting consequence: Linearized Navier-Stokes hydrodynamics provides a good description of heavy quark's wake down to distance scales of $1/T_0$ away from the heavy quark.

Noronha, Torrieri, Gyulassy, PRC 78, 024903 (2008).
Chesler, Yaffe, PRC 78, 045013 (2008).

How big are the flow and temperature fluctuations created by the heavy quark?

Flow

$$U^\mu = (\sqrt{1+\vec{U}^2}, \vec{U})$$

One can show that

$$\boxed{U^i = \frac{T^{0i}}{4p_0} \sim \mathcal{O}(\sqrt{\lambda}/N_c^2)}$$

Local temperature

$$T(X) = T_0 + \Delta T(X)$$

$$\boxed{\Delta T(X)/T_0 \sim \mathcal{O}(\sqrt{\lambda}/N_c^2)}$$

III Computation of Away-side Angular Correlations

Ideally, it would be great if we had an expanding background. Bjorken-expanding as well as radially expanding plasma backgrounds can be constructed.

See Janik, Peschanski, PRD 73, 045013 (2006).
Friess et al., JHEP 0704, 080 (2007).

However, here we use the available data from the current state of the art AdS/CFT calculations for a static background

We use the numerical results for T_{00} and T_{0i}

S. Gubser, S. Pufu, and A. Yarom, PRL 100, 012301 (2008).

Cooper-Frye

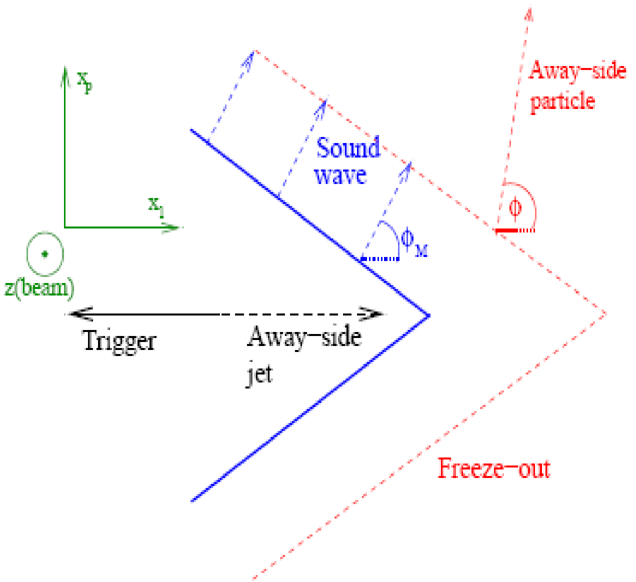
Obtain $U^{\mu}(X) \quad T(X)$

$$E\frac{dN_i}{d^3p} = \# \int_{\Sigma} d\Sigma_{\mu}\, P^{\mu}\, f_i(X,P)$$

Focusing on the hydrodynamical “far zone” ...

Isochronous freeze-out $$d\Sigma^{\mu} = d^3x\,(1,0,0,0)$$

Massless particles at mid-rapidity y = 0



$$P^{\mu} = \left(p_T, p_T\cos\left(\pi-\phi\right), p_T\sin\left(\pi-\phi\right), 0\right)$$

$$f = \exp\left(P_{\mu}U^{\mu}/T(X)\right)$$

Boltzmann approx.

$$f_{eq} = f|_{U=0,T=T_0}$$

Static background

$$\Sigma_T = V\theta(1-Kn)$$

Defines “far zone”

$$\left.\frac{dN}{p_T dp_T dy d\phi}\right|_{y=0} = \int_{\Sigma_T} d\Sigma_{\mu}\, P^{\mu}\,\left[f(U^{\nu},P^{\nu},T) - f_{eq}\right]$$

Note that in the far zone $\exp\left(P_\mu U^\mu / T(X)\right) = 1 + P_\mu U^\mu / T(X) + \mathcal{O}(\sqrt{\lambda}/N_c^4)$

which leads to

$$\left.\frac{dN}{p_T dp_T dy d\phi}\right|_{y=0} \simeq e^{-p_T/T_0} \frac{2\pi p_T^2}{T_0} \left[\frac{\langle \Delta T \rangle}{T_0} + \langle U_1 \rangle \cos\left(\pi - \phi\right)\right]$$

$$\langle \ldots \rangle = \int_{\Sigma_T} dx_1 dx_\perp x_\perp \ldots$$

Global moments

The hydrodynamic “far zone” only gives a broad bump at $\phi = \pi$

- The Mach and diffusion wakes that are present in this region do not lead to interesting structures in the supergravity approximation.

Thus, since the Head has been subtracted any non-trivial shoulder structure can only come from the Neck region !!!!

While we know that CF may not be applicable in the Neck, we hope that some of its features, such as its strong flow, can be roughly described using CF.

Neck zone defined by

$$\Delta\varepsilon/\varepsilon_0 > 0.3$$

$$\cos\phi_{peaks} \neq \frac{c_s}{v}$$

Violates Mach's law!

NGT, arXiv:0807.1038 [hep-ph]

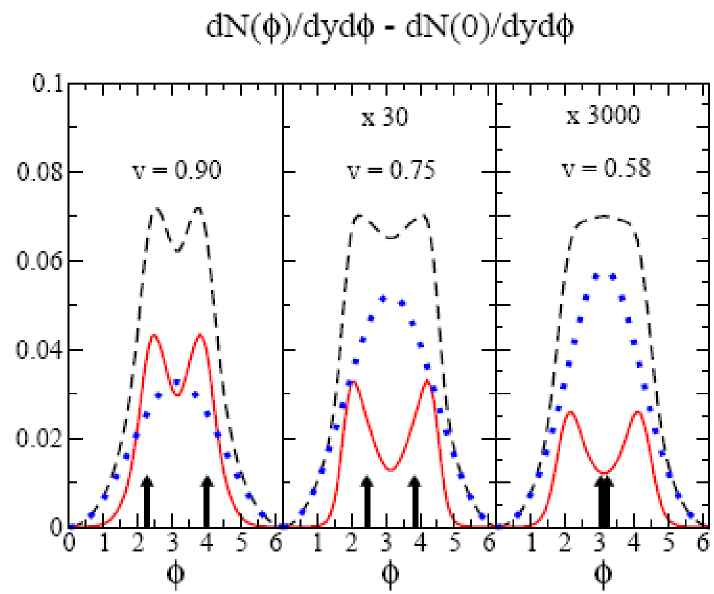


FIG. 2: (Color online) Mid-rapidity azimuthal away side associated angular distribution from the Cooper-Frye freeze-out of the AdS/CFT string drag model $(T(x), \vec{U}(x))$ fields from [15]. Three cases for various heavy quark jet velocity and associated hadron transverse momentum ranges, $1 : (v/c = 0.9, p_T/\pi T_0 =$ 4-5), $2 : (v/c = 0.75, p_T/\pi T_0 =$ 5-6), and $3 : (v/c = 0.58, p_T/\pi T_0 =$ 6-7), are compared. Note the scale factors in the plots. The short arrows show the expected Mach angles. The yields from the Neck region (solid red), Mach and diffusion zones (dotted blue), and the sum from all contributions (dashed black) are shown in this plot.

IV Conclusions & Outlook

- Away-side angular correlations associated with identified heavy quark jets will provide a critical test of the Mach cone hypothesis.

- Our results indicate that the yield from the non-equilibrium Neck zone could imitate Mach cone-like correlations, without, however, the dependence of the angle on the jet velocity as expected from Mach's law. Observation of non-Mach conical correlations associated with tagged heavy quark jets of different velocities could provide additional support for the non-perturbative dynamics implied by AdS/CFT.

- Even the nice and apparently simple conical emission scenario displays several different components (Head, Neck ...). This interesting and complex multicomponent structure makes our life more complicated but its presence is to expected on general grounds and, thus, cannot be neglected in theoretical analyzes.

IV Conclusions & Outlook

- More realistic AdS/CFT setup is needed: expanding medium, phase transition, confinement ... However, due to energy-momentum conservation, we expect that the strong conical flow showed by the Neck should appear in the final away-side angular correlations.

- The effects of fluctuations of the trailing string on the near-quark energy-momentum tensor still need to be investigated.

Back-up slides

Bulk Freeze-out

Based on Betz, Gyulassy, JN, Torrieri, arXiv:0807.4526 [hep-ph]

Bulk momentum distribution

(Bowling ball freeze-out)

$$\frac{dS}{d\cos\theta} = \sum_{cells} |\vec{\mathcal{P}}_c| \delta\left(\cos\theta - \cos\theta_c\right)$$

$$= \int d^3\mathrm{x}\, |\mathbf{M}(X)| \delta\left(\cos\theta - \frac{M_x(X)}{|\mathbf{M}(X)|}\right)\Big|_{t_f}$$

Some comments ...

- We are assuming that the strongly-coupled results computed in SYM can be used to understand the sQGP ...

- Obviously, the decoupling scenario assumed by CF is not justified in a static medium. In any case, for a static medium if anything only isochronous CF makes sense.

- The static medium approximation makes it possible to distinguish the physics in the three different regions (Head, Neck, Far zone).

- In general, CF should be ok in the "far zone" (where the system displays hydrodynamic behavior).

- In the Neck zone CF freeze-out may not be the best approximation because there the strong influence of the the head's color fields.

- Head zone yield is not taken into account in the away-side correlations.

Di-Jet Correlations in pQCD x AdS/CFT

Based on Betz, Gyulassy, JN, Torrieri, arXiv:0807.4526 [hep-ph]

(3+1) Ideal hydro $$T^{\mu\nu} = (\varepsilon + p)U^\mu U^\nu - pg^{\mu\nu}$$

$$\boxed{\partial_\mu T^{\mu\nu} = S^\nu}$$

pQCD-based source

$$S^\mu(X) = (S^0(X), \mathbf{S}(X))$$

Computed by R. Neufeld, PRD 78, 085015 (2008)
Neufeld, Muller, Ruppert, PRC 78, 041901 (2008).

A snapshot of the dynamics

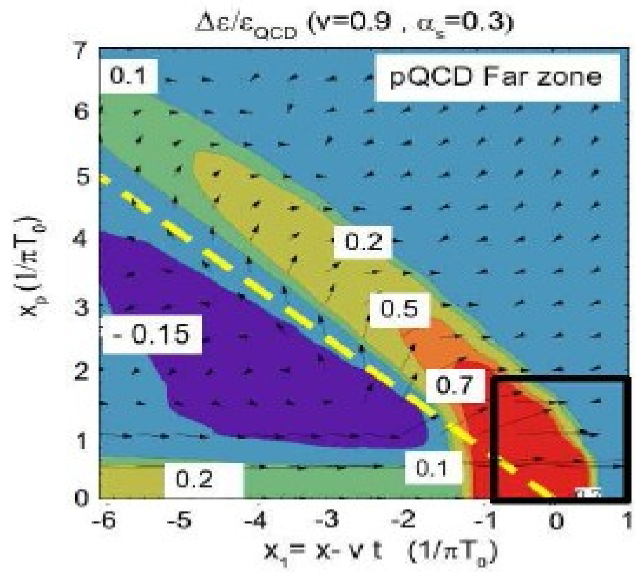


FIG. 1: (Color online) The fractional energy density perturbation $\Delta\varepsilon/\varepsilon_0 \equiv \varepsilon(x_1, x_p)/\varepsilon_0 - 1$ (in the lab frame) due to a heavy quark with $v = 0.9$ in a QCD plasma of temperature $T_0 = 200$ MeV. The induced fluid stress was calculated using 3+1D hydrodynamics [25] with the anomalous pQCD source of Neufeld [20] (left panel) and AdS/CFT [5] (right panel). A trigger jet (not shown) moves in the $-\hat{x}$ direction. The away-side jet moves in $\hat{x}$ direction and contours of $\Delta\varepsilon/\varepsilon_0 = -0.15, 0.1, 0.2, 0.5, 0.7$ are labeled in a comoving coordinate system with $x_1 = x - vt$ and the transverse radial coordinate x_p in units of $1/\pi T_0 \approx 0.3$ fm after a total transit time $t = 5\text{fm/c} = 14.4/(\pi T_0)$. The ideal Mach cone for a point source is indicated by the yellow dashed line in the $x_1 - x_p$ plane. See Fig. 2 for a zoom of the Neck region inside of the black box.

Comparing the Necks in

pQCD and AdS/CFT

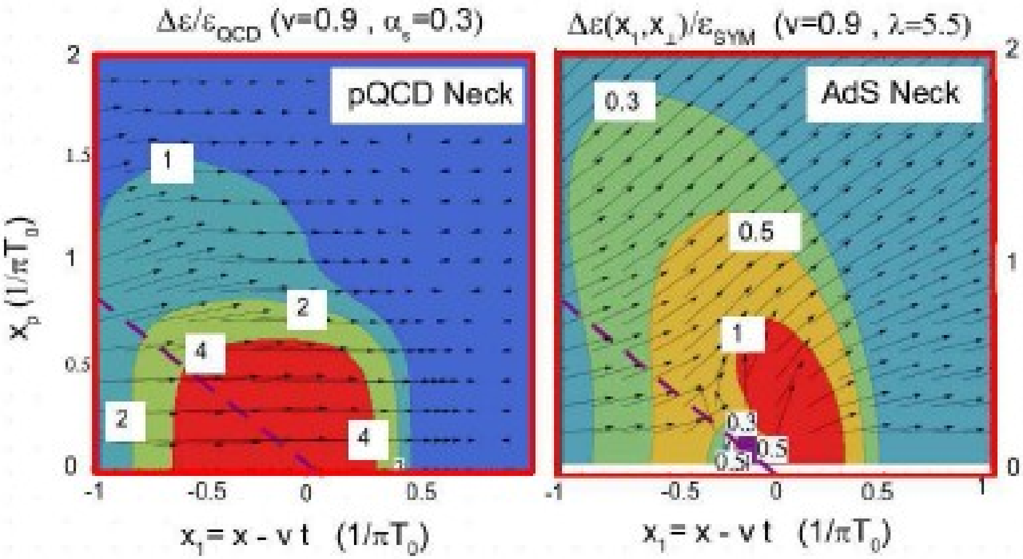
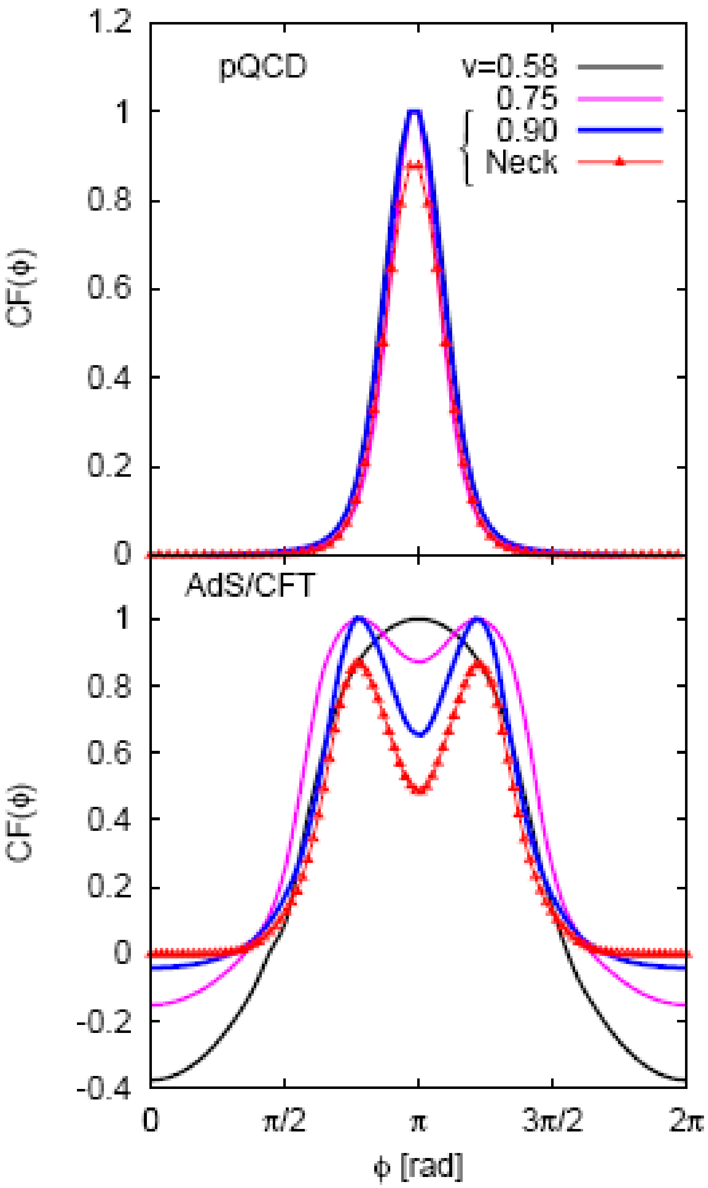


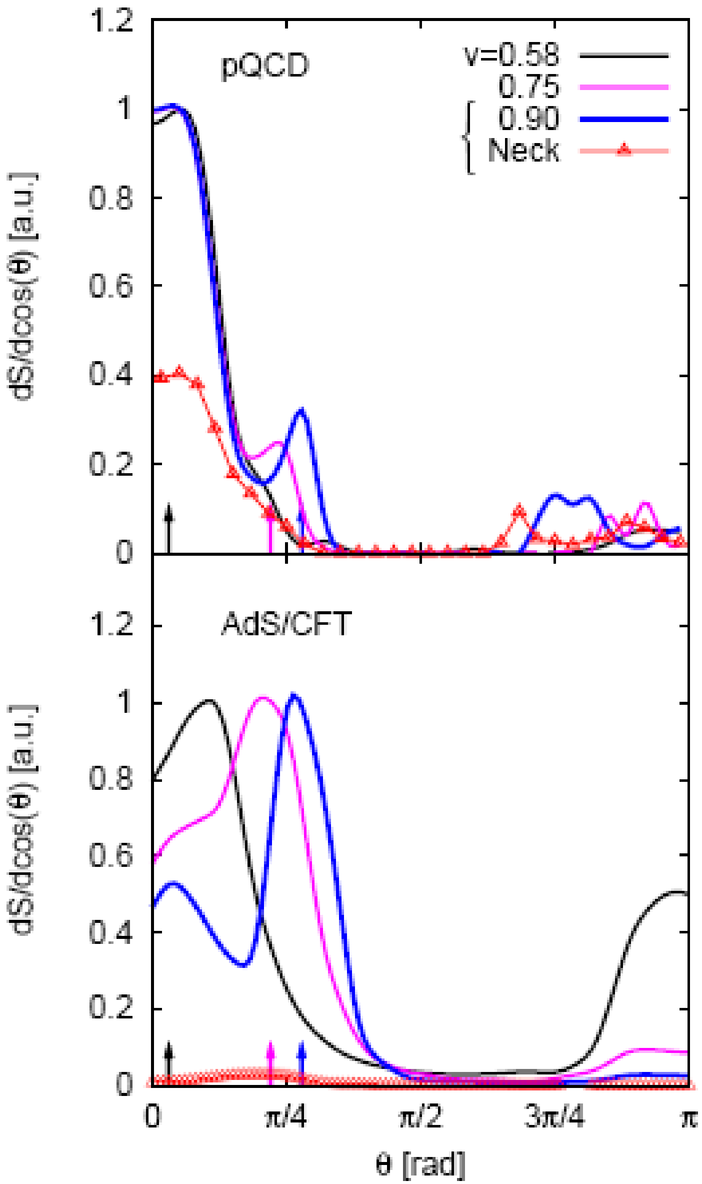
FIG. 2: (Color online) A magnified view of the near "Neck" zone shows the relative local energy density perturbation $\Delta\varepsilon/\varepsilon_0$ and fluid flow directions induced by a heavy supersonic quark jet moving with $v = 0.9$. As in Fig.1, the pQCD contours were computed using 3+1D hydrodynamics [25] sourced by [20] (left panel). The AdS/CFT Neck zone [5] (right panel) uses numerical tables from [7] . The purple dashed line indicates the ideal far zone point source shock angle. The heavy quark is at the origin of these comoving coordinates. The arrows indicate both direction and relative magnitude of the fluid flow velocity. The numbers in the plot label the contours of constant $\Delta\varepsilon/\varepsilon_0$. Note that $\Delta\varepsilon/\varepsilon_0$ is larger in pQCD but that the transverse flow generated near the quark is much stronger in the AdS/CFT model.



Isochronous Cooper-Frye Freeze-out

FIG. 4: (Color online) Normalized (and background subtracted) azimuthal away-side jet associated correlation after Cooper-Frye freeze-out $CF(\phi)$ (see Eq. 9) for pQCD (top) and AdS/CFT from [5] (bottom). Here $CF(\phi)$ is evaluated at $p_T = 5\pi T_0 \sim 3.14$ GeV and $y = 0$. The black line is for $v = 0.58$, the magenta line for $v = 0.75$, and for the blue line $v = 0.9$. The red line with triangles represents the Neck contribution for a jet with $v = 0.9$.

After CF freeze-out, one does not find a double -peak structure in the away-side in pQCD.



Bulk momentum distribution

FIG. 3: (Color online) The (normalized) momentum weighted bulk flow angular distribution as a function of polar angle with respect to the away-side jet is shown for $v = 0.58$ (black), $v = 0.75$ (magenta), and $v = 0.90$ (blue) comparing pQCD anomalous chromo-hydrodynamics to the AdS/CFT string drag [6, 7] model analyzed in Ref. [5]. The red line with triangles represents the Neck contribution for a jet with $v = 0.9$ and the arrows indicate the location of the ideal Mach-cone angle given by $\cos\theta_M = c_s/v$, where $c_s = 1/\sqrt{3}$.

The AdS/CFT Correspondence

Maldacena's conjecture, 1998

$\mathcal{N} = 4$ SYM is equivalent to string theory on $AdS_5 \otimes S_5$

"Definition of the duality"

Witten, 1998;
Gubser, Klebanov, Polyakov, 1998

$$Z_{string}\left[\Phi(x,r)\Big|_{r\to\infty} = \phi_0(x)\right] = \langle e^{\int d^4x \mathcal{O}(x)\phi_0(x)}\rangle_{CFT}$$

- Lorentz invariance
- Match conformal dimension
- Use conserved quantities
- Gauge invariant observables
- Euclidean space

Bulk		Boundary
$g_{\mu\nu}$	$\Longleftrightarrow$	$T^{\mu\nu}$
Dynamical gravity		Translational invariant gauge theory

$\mathcal{N} = 4$ SU(Nc) Supersymmetric Yang-Mills

$$\beta(g_{SYM}) = 0$$

- 16 supercharges + extra 16 due to conformal invariance.
- SU(4) R-symmetry (rotates the scalars and the fermions).
- Global SO(6) symmetry.

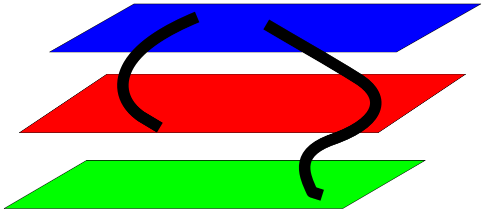
A^a_μ	ψ	ϕ^I $\quad I = 1, \ldots, 6$
Gauge bosons	4 fermions	Scalars

All in the adjoint representation of SU(Nc)

$$L = \frac{1}{g^2} Tr \left[F^2 + \ldots \right]$$

superpartners

Nc D3-branes



The duality at finite temperature (near extremal black brane)

$$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{r^2\,f}dr^2$$

$f = 1 - r_0^4/r^4$ Horizon at $r = r_0$ Black brane

By checking that the Euclidean continuation of the metric is regular at $r = r_0$

Black hole temperature (plasma temperature)

$$T_0 = \frac{1}{4\pi}\sqrt{-g'_{tt}\,g'^{rr}}\Big|_{r=r_0} = \frac{r_0}{\pi R^2}$$

Note that in this case the system is always in the deconfined state.

Entropy density: The Stefan-Boltzmann limit for $\mathcal{N} = 4$ SYM

$$s_{free} = \frac{2}{3}\pi^2 N_c^2 T_0^3 \qquad \lambda \ll 1$$

What about the limit $N_c \to \infty \qquad \lambda \gg 1$?

Bekenstein-Hawking formula: $s_{BH} = \dfrac{a}{4G_{10}}$

$$A = a\, V_3 = \int d^3\vec{x} \int_{S_5} d^5\Omega \sqrt{-det\, G_{\mu\nu}} \longrightarrow a = r_0^3\, \pi^3\, R^2$$

$$\boxed{s_{BH} = \frac{\pi}{2} N_c^2\, T_0^3 = \frac{3}{4} s_{free}}$$

Note the “famous” prefactor ...

In the Neck zone the stress perturbation can be comparable to the background !!!!

How does one define the Neck region?

Extremely close to the quark -> Lorentz boosted Coulomb field stress $\sqrt{\lambda}/|x|^4$

"Head zone"

J. J. Friess et al., PRD 75, 106003 (2007).

Hydrodynamics must fail in the Head zone!!!

Near field zone: Field effects from the Head are important $T_Y^{\mu\nu}(X)$

Computed analytically by Yarom, PRD 75, 105023 (2007); Gubser and Pufu, NPB 790, 42 (2008).

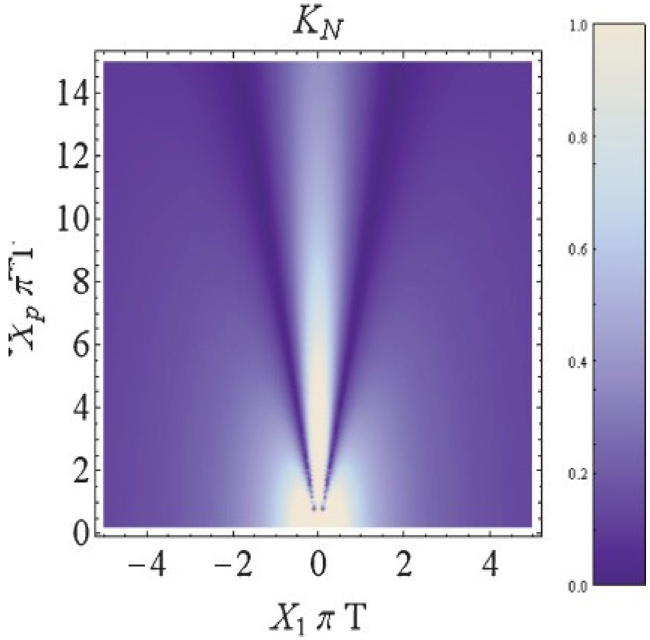
Hydrodynamics is valid when the Knudsen number $Kn = l_{MFP}/L \ll 1$

We define then

$$\boxed{Kn(X) = \Gamma_s |\vec{\nabla}.\vec{S}_Y|/|\vec{S}_Y|}$$

$$S_Y^i \equiv T_Y^{0i}$$

$v = 0.99$



Knudsen zone

$$\delta T^{\mu\nu}_{Kn}(X) \equiv \theta(Kn(X) - 1) T^{\mu\nu}_{Y}(X)$$

$$\delta T^{\mu\nu}_{Kn} \sim \frac{\sqrt{\lambda} T_0^2 \zeta^{\mu\nu}}{x_\perp^2 + \gamma^2 x_1^2}$$

Inside this region local equilibrium cannot be maintained.

Noronha, Torrieri, Gyulassy, PRC 78, 024903 (2008).

Head zone can be determined by equating $\varepsilon_C(x_1, x_\perp) = \varepsilon_Y(x_1, x_\perp)$

Dominguez et al, NPA 811, 197 (2008).

Lorentz contracted pancake $\Delta x_{1,C}\ \pi T_0 \sim 1/\gamma^{3/2}$ $\Delta x_{\perp,C}\ \pi T_0 \sim 1/\gamma^{1/2}$